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ORIGINAL ARTICLE

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Manufacture of oriented board using mild steam treatment of plant fiber bundles

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Abstract This study investigated the effects of mild steam treatment (0.1 MPa for 2 h) of natural bio-based fibers and orientation (0° and 90°) of those fibers in various fiberboards. Ramie bast, pineapple leaf, and sansevieria fiber bundles were used as materials. The composite fiberboards were prepared using phenol–formaldehyde (PF) resin. To investigate the effect of mild steam treatment on wettability, contact angles of PF resin to the fiber were measured. The mechanical properties of the boards were examined as well as their dimensional stability. The contact angle data showed that mild steam treatment was effective in improving the wettability of fibers. Unioriented steam-treated boards showed better performance of internal bond (IB), moduli of rupture (MOR) and elasticity (MOE), thickness swelling (TS), and water absorption (WA) than other boards. Unioriented steam-treated sansevieria board with longitudinal fiber direction showed higher average values of MOR (403 MPa), MOE (39.2 GPa), and IB (1.33 MPa) and lower values of TS (5.15%) and WA (8.68%) than other boards. The differences in the mechanical properties and dimensional stability of boards were found mainly due to the differences in the ratios of fiber fraction of the boards to the density of the fiber bundles.

Key words Plant fiber · Steam treatments · Oriented fiberboard · Mechanical properties · Dimension stability

Introduction

The utilization of the pineapple, ramie, and sansevieria fibers mixed with thermosetting resins, thermoplastic resins, biodegradable polymers, and cellulose for the production of composite products has been developed worldwide.[1–4] Mangal et al.[5] found that the thermal properties of composite made from pineapple leaf fiber randomly mixed with phenol–formaldehyde (PF) resin decrease with the increase of fiber contents. Shihong et al.[6] found that the tensile strength of ramie fibers soaked in epoxy resin and laminated with alternate aluminum sheet is more than 20% greater than that of unreinforced aluminum. Recently, the government of Hong Kong selected sansevieria fiber as one of the fibers for extensive application of so-called green roofs.[7]

Velasquez et al.[8] found that the steam-pretreated *Miscanthus sinensis* exploded with low temperature and steam pressure showed higher mechanical properties of binderless fiberboard than that obtained when using high temperature and steam pressure in the pretreatment. Han et al.[9] also found that the low-pressure steam treatment of reed and wheat straw gave higher dimensional stability in medium density fiberboard (MDF) than that obtained using high-pressure steam treatment.

Fiberboard manufactured from low molecular weight (LM_W) PF resin mixed with high molecular weight (HM_W) PF resin showed the higher mechanical properties than fiberboard manufactured from either LM_W PF resin or HM_W PF resin alone.[10,11] Unidirectionally oriented fiber mats on the board showed higher mechanical properties than fiber mats with random orientation or other orientations.[11–14]

Based on our previous reports,[15,16] pineapple leaf fiber, sansevieria leaf fiber, and ramie bast fiber treated with mild steam showed excellent mechanical properties. On the other hand, the approach of using long fiber bundles treated with mild steam and layered with different orientations on the mats, which is expected to increase the interlocking of the fibers and mechanical properties of the board, have not been fully exploited. The aim of this study was to evaluate the mechanical properties of oriented boards obtained from the mild steam treatment of ramie, pineapple, and sansevieria fibers for use as construction materials.

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Materials and methods

Materials

Three decorticated nonwood plant fiber bundles were used as raw materials. They were pineapple [*Ananas comosus* (L.) Merr] leaf fiber, sansevieria (*Sansevieria trifasciata* Prain) leaf fiber from Subang, West Java, Indonesia, and ramie [*Boehmeria nivea* (L.) Gaudich] bast fiber from Wonosobo, Central Java, Indonesia. The fibers were air-dried to a moisture content of 6% to 8%.

Fiber preparation by combing process

The fibers were first cut to 35 cm in length. Afterward the fibers were straightened on a table by manually combing them, and finally were sorted by length. The main purposes of this procedure were to homogenize the fibers in length and to obtain straight fibers. The fibers were weighed for each layer of board. Then the fibers were distributed and clipped using a wood stick prior to mild steam processing.

Mild steam treatment

The fibers were steamed in a vertical direction by using boiling water in a tank covered with screen-plaited bamboo at a steam pressure of about 0.1 MPa for 2 h. The steam-treated fibers were air-dried to a moisture content of 6%–8% prior to board manufacture.

Resin solution preparation

Two types of PF resin were chosen for impregnation and adhesive purposes: low molecular weight (LM_W) PF resin type PL-3725, and high molecular weight (HM_W) PF resin type PL-2818 (Gunei Chemical). Both resins were mixed and an impregnation solution of the resins was prepared by adding methanol and water to decrease the viscosity. The weight ratio of LM_W : HM_W : methanol : water was 0.5 : 0.5 : 1 : 1. The characteristics of LM_W, HM_W, and mixed LM_W/HM_W resins are shown in Table 1.

Measurement of wettability

Wettability is expressed as the advancing contact angle of PF resin solution on the outer surface of fibers. Prior to contact angle measurement, fiber specimens were conditioned at 60% relative humidity (RH) and 20°C for 1 week. The contact angle was measured with a scalar contact anglemeter at room temperature. An aliquot (1 μl) of prepared PF resin solution was dropped onto the surface of the fibers with a micropipette. A photograph was taken 60 s after the solution dropped. The contact angle was calculated with the height and chord of the droplet measured.[9] Five measurements were conducted for each sample. The contact angle and other characteristics of the fibers are given in Table 2.

Board preparation

Boards measuring 300 × 300 × 4 mm with a target density of 0.8 g/cm^3 were manufactured by using untreated and mild steam-treated fiber bundles. The untreated and mild steam-

Table 1. Characteristics of low molecular weight (LM_W), high molecular weight (HM_W), and mixed resins

PF resin	Solid content (%)[b]	pH	Specific gravity (g/cm^3)	Viscosity (mPa.s)
LM_w	52.6	8.5	1.021	409
HM_w	72.4	7.0	1.161	12 329
Mixed[a]	12.3	8.0	0.934	120

PF, Phenol–formaldehyde
[a] Mixed resin of LM_w : HM_w : methanol : water in weight ratio of 0.5 : 0.5 : 1 : 1
[b] Measurement of solid content accordiing to ASTM D-4426-01[17]

Table 2. The physical, mechanical, and contact angle properties of untreated and steam-treated plant fiber bundles

Fiber	Density (*D*) (g/cm^3)[a]	Tensile strength (Ts) (MPa)[a]	Specific strength (Ts/*D*) (MPa g^{-1} cm^3)	Contact angle (°)
PU	1.32	635 ± 143	481	63.3 ± 2.4
PS		729 ± 171	552	47.8 ± 2.1
RU	1.38	830 ± 174	601	64.7 ± 2.6
RS		892 ± 163	646	47.3 ± 3.0
SU	0.89	560 ± 99	629	49.6 ± 3.2
SS		697 ± 86	783	44.6 ± 2.9

Data given as averages with 95% confidence interval
PU, Untreated pineapple; PS, steam-treated pineapple; RU, untreated ramie; RS, steam-treated ramie; SU, untreated sansevieria; SS, steam-treated sansevieria
[a] Data from our previous reports[15,16]

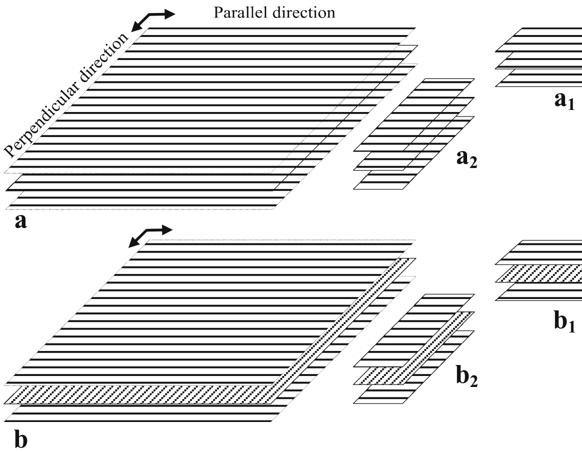

Fig. 1a, b. Layout for manufacturing of plant fiber boards. **a** Unioriented, **b** cross-oriented (a_1 and b_1, parallel direction samples for modulus of rupture (MOR) and modulus of elasticity (MOE); a_2 and b_2, perpendicular direction samples for MOR and MOE

treated fiber webs were dipped into the PF resin solutions. Excess impregnation PF resin was squeezed out by passing the fiber web thorough a pair of rollers. The impregnated fiber webs were dried at room temperature for 12 h to give a resin content of 20% (dry weight) of the fibers.

Thereafter, the fiber mats were laid by manually orienting the impregnated fibers. Two different orientations of board were prepared for each fiber, each in three layers (1:1:1 weight ratio) (Fig 1). The unioriented (0°, Fig. 1a) and cross-oriented (90°, Fig. 1b) mats were consolidated in a laboratory hot press with a specific pressure of 4.5 MPa and at a pressing temperature of 160°C for 15 min.

Prior to the evaluation of fiberboard properties, the fiberboard was conditioned for 2 weeks at 20°C and 65% ± 5% RH and the samples for the tests were prepared. The actual densities of the boards were in the range of 0.78 to 0.90 g/cm^3 with standard deviations of 0.04 to 0.05 g/cm^3. No boards were warped or twisted.

The moisture contents of fiberboards were determined using five specimens (50 × 50 × 4 mm) from each sample and calculated from the weights of specimens in the above conditions. The factorial design used included three factors: fiber species (pineapple, ramie, and sansevieria), fiber type (untreated and steam treated), and board orientation (unioriented and cross oriented). The 12 treatment combinations and 2 replications resulted in 24 boards. The list of treatments and board types and the notation used to describe the samples are shown in Table 3.

Mechanical properties test

The mechanical properties of the boards were measured according to JIS A 5905.[18] The tests included the testing of dry and wet bending strength type B (modulus of rupture; MOR) and modulus of elasticity (MOE) in parallel and perpendicular directions (see Fig. 1), and internal bond strength (IB).

Table 3. Experimental variables in board manufacturing

Code	Board type
PU-0	Unioriented untreated pineapple board
PU-90	Cross-oriented untreated pineapple board
PS-0	Unioriented steam-treated pineapple board
PS-90	Cross-oriented steam-treated pineapple board
RU-0	Unioriented untreated ramie board
RU-90	Cross-oriented untreated ramie board
RS-0	Unioriented steam-treated ramie board
RS-90	Cross-oriented steam-treated ramie board
SU-0	Unioriented untreated sansevieria board
SU-90	Cross-oriented untreated sansevieria board
SS-0	Unioriented steam-treated sansevieria board
SS-90	Cross-oriented steam-treated sansevieria board

Dimensional stability test

Thickness swelling (TS) and water absorption (WA) properties were determined by a simple water soaking test. All samples were prepared according to JIS A 5905. Thickness swelling and water absorption were measured after immersing the samples in distilled water at 20°C for 24 h.

Thickness change (TC) was measured using a wet/dry cycle test.[19] The samples were oven-dried at 60°C for 3 days (OD1), water-soaked at 25°C for 24 h (W1), oven-dried at 60°C for 3 days (OD2), water-soaked at 70°C for 24 h (W2), oven-dried at 60°C for 3 days (OD3), boiled for 4 h (W3), and oven-dried at 60°C for 3 days (OD4).

Observation of fiber orientation in the boards

An optical microscope (Micro Square DS-3USV) was used to investigate the fiber orientation in the unioriented boards.

Results and discussion

Effect of steam treatment on wettability of fibers

Contact angles between resin solution and fiber are shown in Table 2. The contact angles of the outer surfaces of all bundles were reduced after steam treatment. The contact angles decreased about 25% for pineapple leaf, 26% for ramie, and 10% for sansevieria. The steam-treated sansevieria fiber bundles had the lowest contact angles. *F*-Test statistical analysis revealed a significant effect of steam treatment on the contact angle of fibers at the 95% confidence level. This indicates that steam treatment in the studied range had a significant effect on the wettability of the fiber surface.

The improvement of the wettability could be attributed to the removal of wax and pectin from the fiber surfaces.[20] The wax is primarily located in the cuticle and primary wall, and small amounts of residual wax may also form a thin film on the surfaces of the fiber. Other researchers[21] have found that the wax removed from the surface of the fiber by steam treatment above 60°–70°C. Lawther et al.[22] reported that

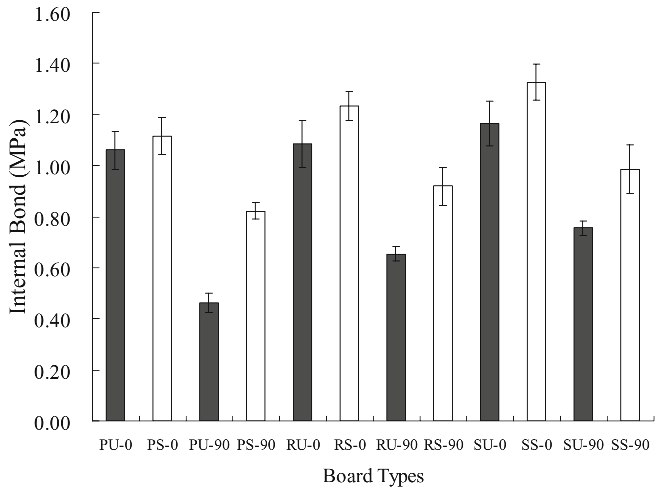

Fig. 2. Internal bond (IB) strength of boards for 12 different types of board. See Table 3 for explanation of sample codes

steam treatment removed some portion of pectin substances and hemicellulose from wheat straw. The pectin substances and high content of hemicellulose in nonwood lignocellulosic materials usually result in less adhesion between resin adhesives and these materials. The extraction of these substances would certainly contribute to the enhancement of board properties.

The wettability of the material also depends on the surface morphology and its polarity.[23] Based on previous research,[16] the surface of steam-treated fiber is smoother than untreated fiber. This is due to removal of some material (wax, pectin) from the fiber surface, which allows the resin to spread more easily on the fiber surface. Therefore, the contact angles of steam-treated fibers become lower than those of untreated fibers.

Internal bond strength

The IB values of oriented board are shown in Fig. 2. The IB of unioriented (0°, Fig. 1a) and cross-oriented (90°, Fig. 1b) boards increases when the fibers are treated with mild steam. The IB of cross-oriented boards showed lower values than unioriented boards.

The highest IB value was 1.33 MPa and 1.23 MPa for SS-0 and RS-0, respectively (see Table 3 for explanation of sample notation). The lowest value was 0.65 MPa and 0.45 MPa for RU-90 and PU-90, respectively. Thus, the steam treatment and unidirectional orientation of fiber in fiberboard effectively increased the bonding strength of the boards.

The relatively lower IB strength for cross-oriented untreated boards was largely attributed to the lower fiber contact area and bonding strength between fibers and the intertwisting of fibers.[24,25] The IB properties of pineapple and ramie boards are lower than those of sansevieria boards. This may be because the compaction ratios (ratio of board density to material density)[26] of pineapple and ramie boards are lower than those of sansevieria boards. The IB of all board types was higher than that of kenaf board (0.44 MPa)[11] on the same density level.

Bending properties

The flexural properties of pineapple, ramie, and sansevieria boards in different types of boards and under different specimen conditions are given in Fig. 3. It can be observed from the figure that the dry parallel and perpendicular average MOR values of the boards increased when the boards were made from steam-treated fibers. The highest value of dry parallel MOR was 403 MPa for SS-0 and 386 MPa for RS-0, while the highest values of dry perpendicular MOR was 67 MPa for RS-90 and 66 MPa for SS-90.

The same trend was also found for wet MOR values. The wet parallel and perpendicular MOR values of the boards increased when the boards were made from steam-treated fibers. The highest value of wet parallel MOR was 176 MPa for SS-0 and 159 MPa for RS-0, while the highest value of wet perpendicular MOR was 29 MPa for PS-90 and 27 MPa for SU-90. These dry parallel and perpendicular MOR values of boards are higher than that for kenaf board[11,27] on the same density level.

Similar results were also found in dry/wet parallel–perpendicular relationships for MOE of boards. The highest value of dry parallel MOE was 39.2 GPa for SS-0 and 34.2 GPa for RS-90, while the highest value of dry perpendicular MOE was 8.5 MPa for SU-90 and 7.8 MPa for SS-90. On the other hand, the highest value of wet parallel MOE was 19.2 GPa for SS-0 and 16.2 GPa for RS-90, while the highest value of dry perpendicular MOE was 4.1 MPa for SU-90 and 3.8 MPa for PS-90.

Generally, the dry/wet MOR and MOE of unioriented boards were significantly higher than those for cross-oriented boards for samples cut parallel with main board orientation (samples a_1 and b_1 in Fig. 1). The dry/wet MOR and MOE perpendicular to main board orientation of unioriented boards was also significantly different to cross-oriented boards (samples a_2 and b_2 in Fig. 1).

The parallel to perpendicular ratio of dry MOR on unioriented boards was in the range of 1:14 to 19, while the parallel to perpendicular ratio of dry MOR on cross-oriented boards was in the range of 1:4 to 5. The highest parallel to perpendicular ratio of dry MOR was 1:19 for SU-0 and 1:18 for SS-0. The parallel to perpendicular ratios of wet MOR of boards were also observed with similar results.

The parallel to perpendicular ratio of dry MOE on unioriented boards was in the range of 1:19 to 24, while the parallel to perpendicular ratio of dry MOE on cross-oriented boards was in the range of 1:3 to 4. The highest parallel to perpendicular ratio of MOE was 1:24 for SU-0 and and 1:23 for SS-0. The parallel to perpendicular ratios of wet MOE of boards were also observed with similar results. Those ratios were larger than those for oriented fiberboard made from kenaf fiber (MOR and MOE = 1:7.9

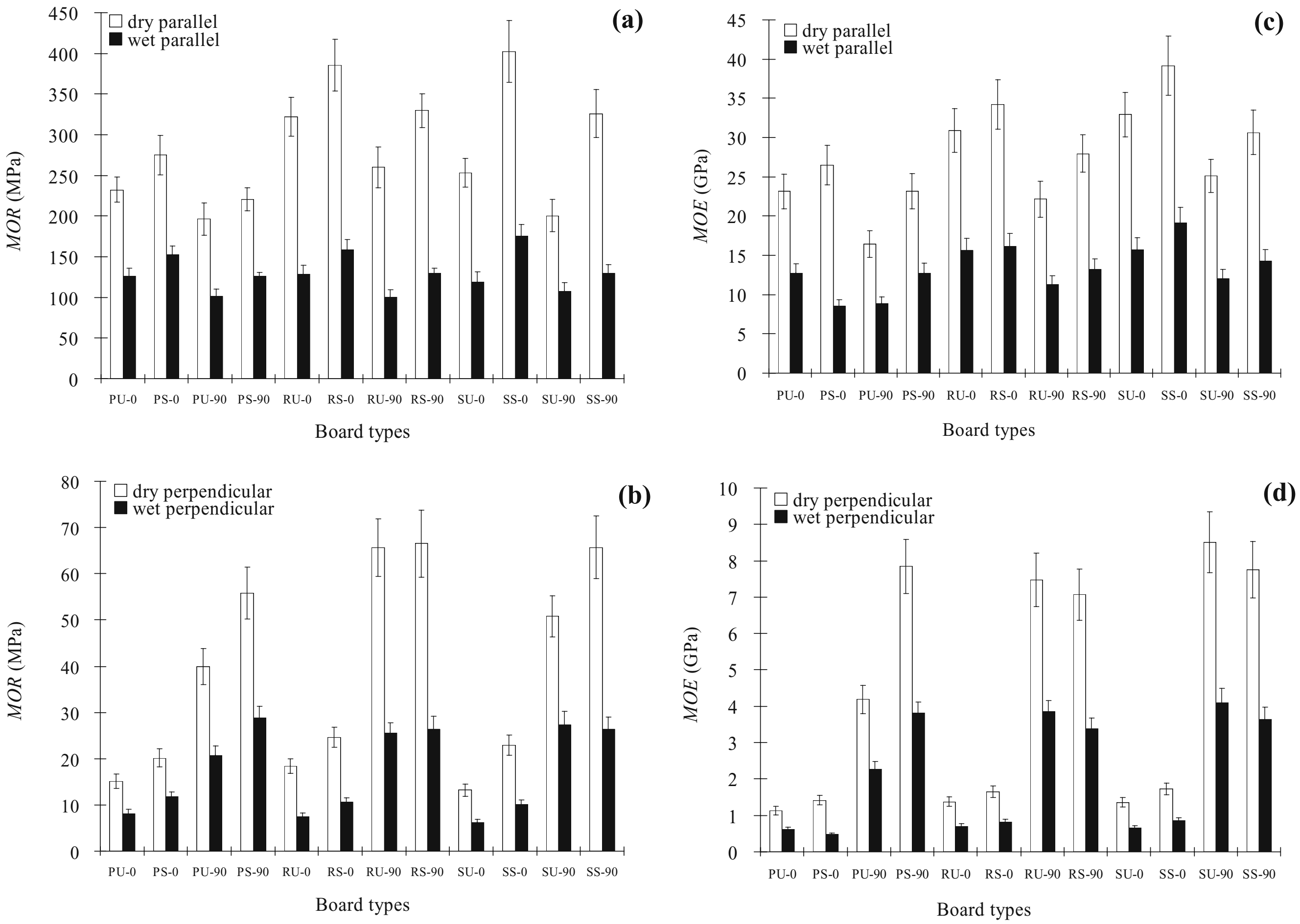

Fig. 3a–d. MOR and MOE of 12 types of boards. **a** Dry/wet parallel MOR, **b** dry/wet perpendicular MOR, **c** dry/wet parallel MOE, **d** dry/wet perpendicular MOE

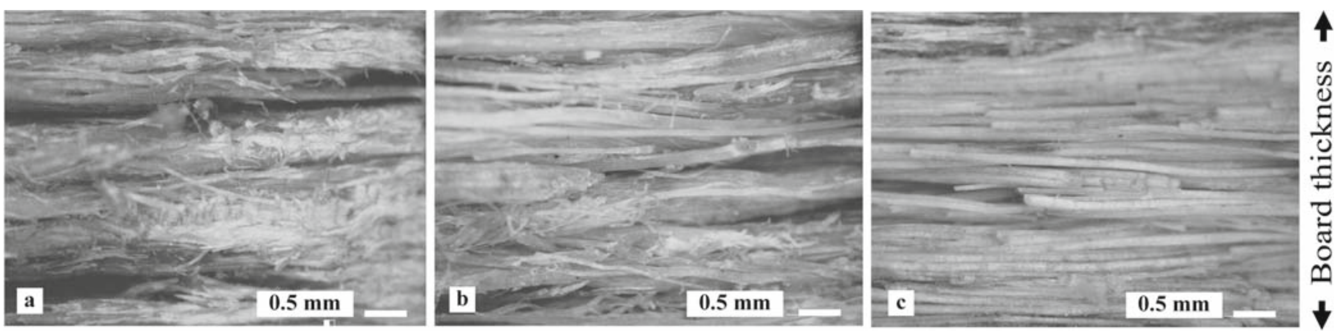

Fig. 4a–c. Fiber orientation in unioriented boards (thickness view). **a** Pineapple board, **b** ramie board, **c** sansevieria board

and 1:13.4).[27] The higher parallel to perpendicular ratios for MOR and MOE were largely attributed to the high orientation of fiber in the board. Thus, the combing process resulting highly oriented fiberboard.

The sansevieria fiber on the board was joined more closely than pineapple and ramie fibers, as shown in Fig. 4. It can be observed that the orientation and unit of sansevieria fiber bundles on the board more obvious than those of pineapple and ramie fibers. This is because the compression sets of sansevieria fiber in the pressing process are bigger than those for pineapple and ramie fiber due to the lower density of sansevieria fiber used in the experiment.

Figure 5 shows the relationship between ratios of fiber fraction of unioriented board to the density of fiber bundles and ratios of unioriented board MOR to tensile strength of fiber bundles. The fiber fraction were calculated by the density of board (0.8 g/cm^3) times the weight fraction of fibers on the board (0.8). Therefore, the ratios of fiber substances (0.64 g/cm^3) on unioriented board to density of fiber

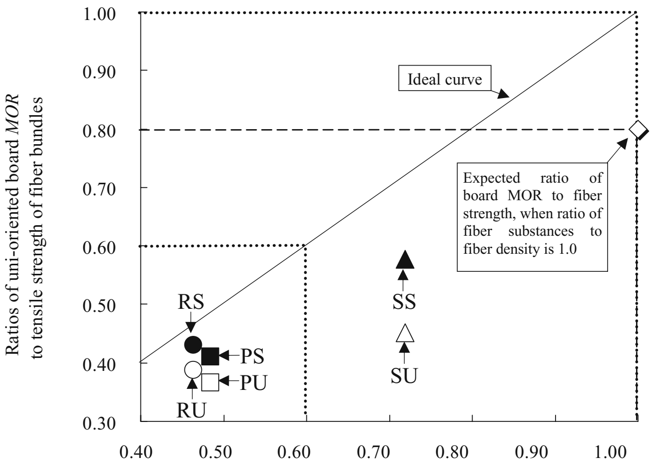

Fig. 5. Relationship between ratio of fiber fraction in unioriented board to fiber density and ratio of unioriented board MOR to tensile strength of fiber

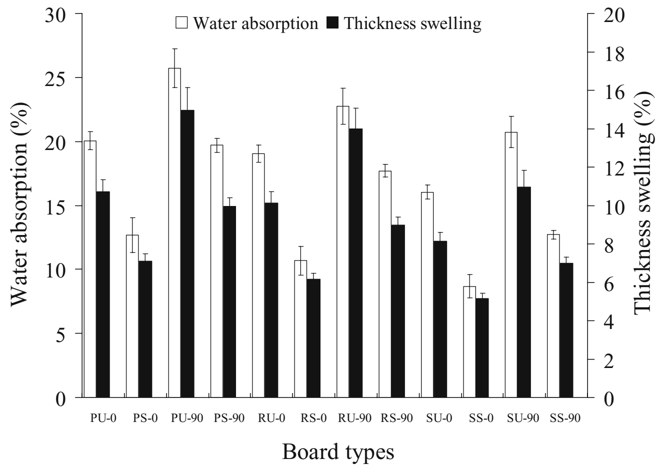

Fig. 6. Thickness swelling and water absorption of boards after immersion in water at 20°C for 24 h. See Table 3 for explanation of sample codes

bundles (in Table 2) were 0.46, 0.48, and 0.72 for ramie, pineapple, and sansevieria boards, respectively. Based on the data in Fig. 3 and Table 2, the ratios of unioriented board MOR values to tensile strength of fiber bundles were calculated.

The ratios of MOR values of steam-treated boards to the tensile strengths of fiber bundles are higher than those of untreated boards. The highest ratios obtained in this study were 0.58 and 0.45 for steam-treated and untreated sansevieria boards, respectively. The ratios of board strengths to fiber tensile strengths increased with increasing ratios of fiber fraction on the board to fiber densities. The board MOR increased by 12%, 11%, and 28% for pineapple, ramie and sansevieria, respectively, when the boards were made from steam-treated fibers. This more than two times increase in the steaming effect for sansevieria board is due to the higher compression set and higher bondability among steamed sansevieria fibers. Figure 5 shows that the MOR values in this experiment reflect 40%–60% and 35%–45% of the respective fiber strength for steam-treated fiber and untreated fiberboards, respectively. In the case of the random oriented particleboards/fiberboards with adhesives, Kawai[28] estimated a bending strength of around 15% of the estimated values of defibrated wood fibers, while a variation of the bending strength of between 5% and 10% in the case of particleboards/fiberboards without adhesives was predicted.

Based on the results of this study, it was calculated that the ratios of fiber fraction to fiber density (board compaction ratio without adhesive) could be 1.0 when the densities of sansevieria, pineapple, and ramie boards are 1.11, 1.65, and 1.73 g/cm^3, respectively. Furthermore, when the ratios of fiber fraction to fiber density are 1.0, it was also calculated that the values of the MOR parallel to the fibers of the unioriented fiberboards without adhesives reach 80% of the fiber strength. Thus, the MOR values obtained in this experiment were much higher than those of boards made from the plant fiber as previously published.[11,24,27]

Dimensional stability

The moisture content (MC) of the each board type was measured after conditioning and it was found that MC varied in the range of 3.2%–4.6%. The extent of thickness swelling after water immersion for 24 h at room temperature is shown in Fig. 6. It was observed that the swelling of the steam-treated boards was lower than for untreated boards, and the swelling of cross-oriented boards was higher than for unioriented boards. The swelling of untreated boards was in the range of 8.1%–15%. When the PF resin was mixed with steam-treated fibers, the swelling was reduced by about 35.6%. Other research[29,30] found that the dimensional stability of fiberboard made from sugarcane and wood chips with high-pressure steam pretreatment was improved over that from untreated fiber. The swelling of unioriented steam-treated boards was in the range of 5.2%–7.1%. The cross-oriented boards made from untreated and steam-treated fibers, repectively, showed higher swelling than the unioriented board for each fiber type. This indicates that the unioriented boards present better performance in integration between fiber and resin.

On the other hand, the water absorption property of the board was lower for board made from steam-treated fibers. The water absorption of steam-treated boards was lower than untreated boards, whereas the water absorption increased to about 38% for cross-oriented board. The lowest water absorption of about 8.9% was found in SS-0.

The thickness changes (TC) of the boards after wet/dry cycles with reference to type of fiber, fiber orientation, and fiber treatment are shown in Fig. 7. The purpose of the TC test is to determine the adhesive performance of the board.

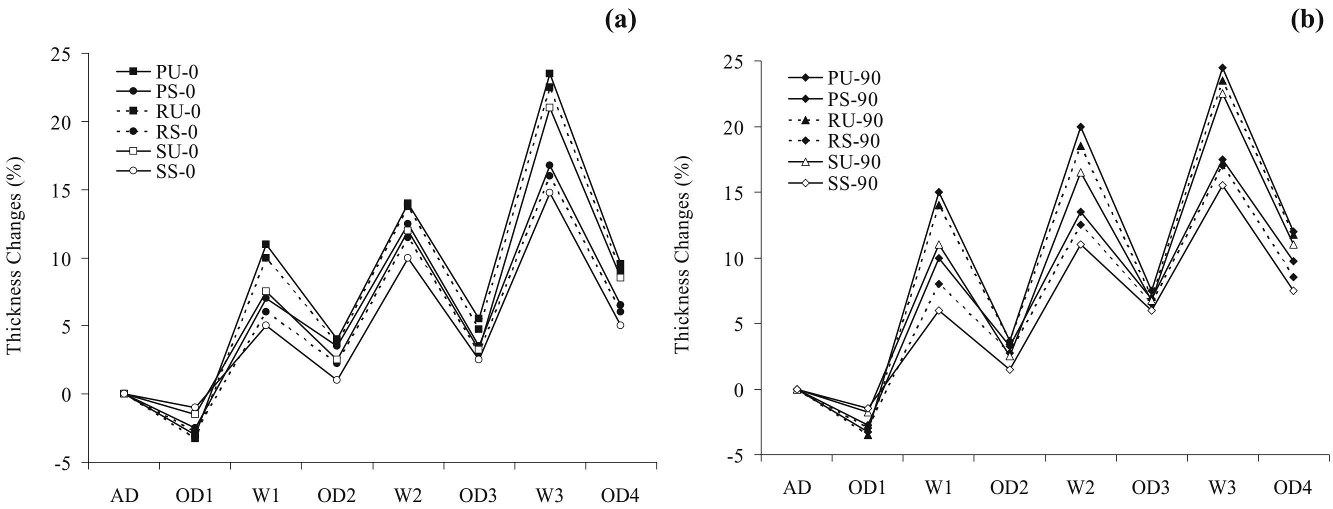

Fig. 7a, b. Thickness changes of boards under wet/dry cycles. **a** Unioriented boards, **b** cross-oriented boards. *AD*, Air dry; *OD*, oven-dry conditions at 60°C for 3 days; *W1*, water soaking at 25°C for 24 h; *W2*, water soaking at 70°C for 24 h; *W3*, boiling for 4 h

The TC values of boards depend on the board bonding strength (in wet and dry condition) and compaction ratios (in wet condition only). The relaxation after alternating cyclic RH exposure has been previously attributed to permanent relaxation of thickness compressive stresses during hot pressing and resin cure. The best TC performance was found in SS-0. The TC for each treatment (W1, W2, or W3) showed the minimum values in steam-treated board, and the values for the oven-dry condition were smaller than those for untreated board.

For pineapple and ramie boards, the compression sets of pineapple fiber and ramie fiber in the pressing process are thought to be very small because the densities of the pineapple and ramie fibers used in the experiment were 1.32 and 1.38 g/cm^3, respectively (Table 2). Therefore, it can be assumed that the TC of the pineapple and ramie boards resulted mainly from disintegration of fibers, which resulted in the decrease of bonding strength from a permanent breaking of resin bonds. Low wettability of pineapple and ramie fibers also contributed to the low bonding property.

Conclusions

Based on the results of this research, the effect of steam treatment and fiber orientation on the properties of oriented pineapple, ramie, and sansevieria boards are summarized as follows:

1. The wettability of fibers was improved with mild steam treatment.
2. The internal bond of oriented boards increased when the fibers were treated with mild steam. The highest internal bond was 1.33 MPa for unioriented steam-treated sansevieria board and the lowest was 0.45 MPa for cross-oriented untreated pineapple board. Thus, steam treatment and uniorientation of fiber are more effective in obtaining high-performance bonding strength of boards.
3. The boards made from steam-treated fibers had higher values of MOR and MOE. The unioriented boards showed higher average values of MOR and MOE than cross-oriented boards. The highest values of MOR and MOE were 403 MPa and 39.2 GPa, respectively, for unioriented steam-treated sansevieria boards. The differences in board MOR and MOE were found to be related to the differences in the ratios of fiber fraction of the board to density of fiber bundles.
4. The highest parallel to perpendicular ratios for MOR and MOE were 1 : 19 and 1 : 23, respectively, for unioriented untreated sansevieria board. This was largely attributed to the high orientation of fiber in the board. Thus, the combing process resulted in highly oriented fiberboard.
5. Mild steam treatment of fibers imparts dimensional stability to the boards. The dimensional stability of steam-treated boards was marginally increased over that of untreated board.

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